NBS TECHNICAL NOTE 682

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Implementation of the Notch Technique as an RF Peak Pulse Power Standard

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Philip A. Simpson and Paul A. Hudson

ABSTRACT

The theory and operation of a standard for measuring rf peak pulse power is described. The standard is based on the "notch" principle. It is constructed in coax for frequencies up to 4.4 GHz, and in WR-90 waveguide (8.2-12.4 GHz). The basic range is 1 to 10 mW but is extendable to cover 10 μW to 10 kW using directional couplers. Risetime of the system is 14 nanoseconds. A comprehensive error analysis is given. The uncertainty in coax is 3 percent and in waveguide is 4 to 6 percent depending upon peak power level.

Key words: Notch wattmeter; pulse-CW equalization; pulse modulated carrier systems; rf peak pulse power.

1. INTRODUCTION

Pulse modulated rf and microwave carrier systems find extensive use in many widespread and diverse fields. Tacan, IFF, air traffic control, radar, radar altimeters, and digital communications are among some of the more prominent areas that use this type of signal. In all of these, for the systems to be most effective and efficient, it is necessary to know that the peak power of the rf signal is within certain prescribed upper and lower limits.

In order to respond to the measurement needs for this segment of the National Measurement System, the NBS developed a laboratory standard for rf peak pulse power based on a sampling-comparison method in 1962 [1], and from this evolved a calibration service which was announced in 1965 [2]. This method was used until 1970 when, for certain advantageous reasons mentioned later, a working standard and calibration system based on the notch wattmeter [3] was developed. This paper describes the system as it is presently employed at NBS.

2. THEORY OF OPERATION

2.1 Basic Principle

Measurement of rf peak pulse power* by the notch wattmeter technique is based on a comparison of the pulse with an auxiliary rf signal of adjustable amplitude, and whose frequency equals the pulse carrier frequency. This comparison includes an adjustment of the amplitude of the CW signal to equal that of the pulse and is carried out in a unique manner. Both the pulse and CW signals are introduced into the same transmission line but

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*In this paper, rf peak pulse power is a contraction of "Peak Pulse Power, Carrier Frequency" which IEEE defines as the power averaged over the carrier cycle which occurs at the maximum of the pulse of power.

are not mixed in the ordinary sense. The CW signal is turned off or "notched" for a time period slightly longer than the pulse duration and the pulse is positioned, timewise, within the notch. A notch occurs for each pulse generated. The combined signals are sampled, typically by a directional coupler, detected with a fast crystal diode and then fed to an oscilloscope for convenient comparison. After the CW signal amplitude has been adjusted to equal that of the peak of the pulse, the power level of the composite signal in the main arm of the coupler is measured using a CW power meter. Thus, peak pulse power measurement is reduced to a measurement of CW power and attenuation which can be performed conveniently and accurately. The rf pulses generated are generally trapezoidal in shape with negligible anomalous excursions. It should be noted that this method permits using pulses with shapes other than trapezoidal. In order to make a measurement all that need be done is align the peak of the pulse (or any other desired point on the displayed waveform) with the top of the notched CW. The response of the instrument under test (IUT) to non-trapezoidal waveforms is not covered in this paper since it is primarily dependent upon the type of instrument and the pulse shape.

System configurations for performing high and low level measurements are shown in figures 1a and 1b. Their operation is as follows. Referring to figure 1a, the output from the rf pulse generator is applied to the IUT through the primary line of coupler A. A known fraction of the power is coupled to the sidearm of coupler A and passes on to the sidearm of coupler B. A fractional sample of this signal is then coupled to the primary line of coupler B, continues on to the monitor coupler M, and finally is absorbed by the bolometer mount.

A low power "notched" CW signal (zero to 10 mW) is delivered to the primary input port of coupler B and is thus added to the existing pulsed signal. The "notch" is generated by means of a fast diode switch modulator which is gated to turn off the CW for a short time interval each time an rf pulse is generated. The duration of the notch is adjusted to be slightly greater than the pulse duration. A sample of the composite signal, which includes the pulse and the notched CW, is coupled to the sidearm of coupler M, detected with a crystal diode, and then viewed on an oscilloscope. By use of adjustable time delays, the pulse can be precisely positioned within the notch of the CW signal as shown in figure 2.

The basic principle of the system is, of course, to allow calculation of the pulse power incident (P_{inc}) upon the IUT from a measurement of CW power. This principle is fundamentally the same as that employed in the familiar bolometer-coupler unit. Accordingly, we have modelled the essential parts of the system as a bolometer-coupler unit as shown in the block diagram of figure 3. Here P_1, P_2, and P_3 represent net powers at the indicated terminating planes; Γ_1, Γ_2, and Γ_3 represent the complex reflection coefficients at the same places; and η_{21}, η_{32}, and η_m are the efficiencies of coupler B, coupler M, and the bolometer mount, respectively. The circled numbers refer to the appropriate ports of the various couplers as determined from figures 1a and 1b. This model will aid in giving a better understanding of the system theory and operation as well as simplifying the error analysis.

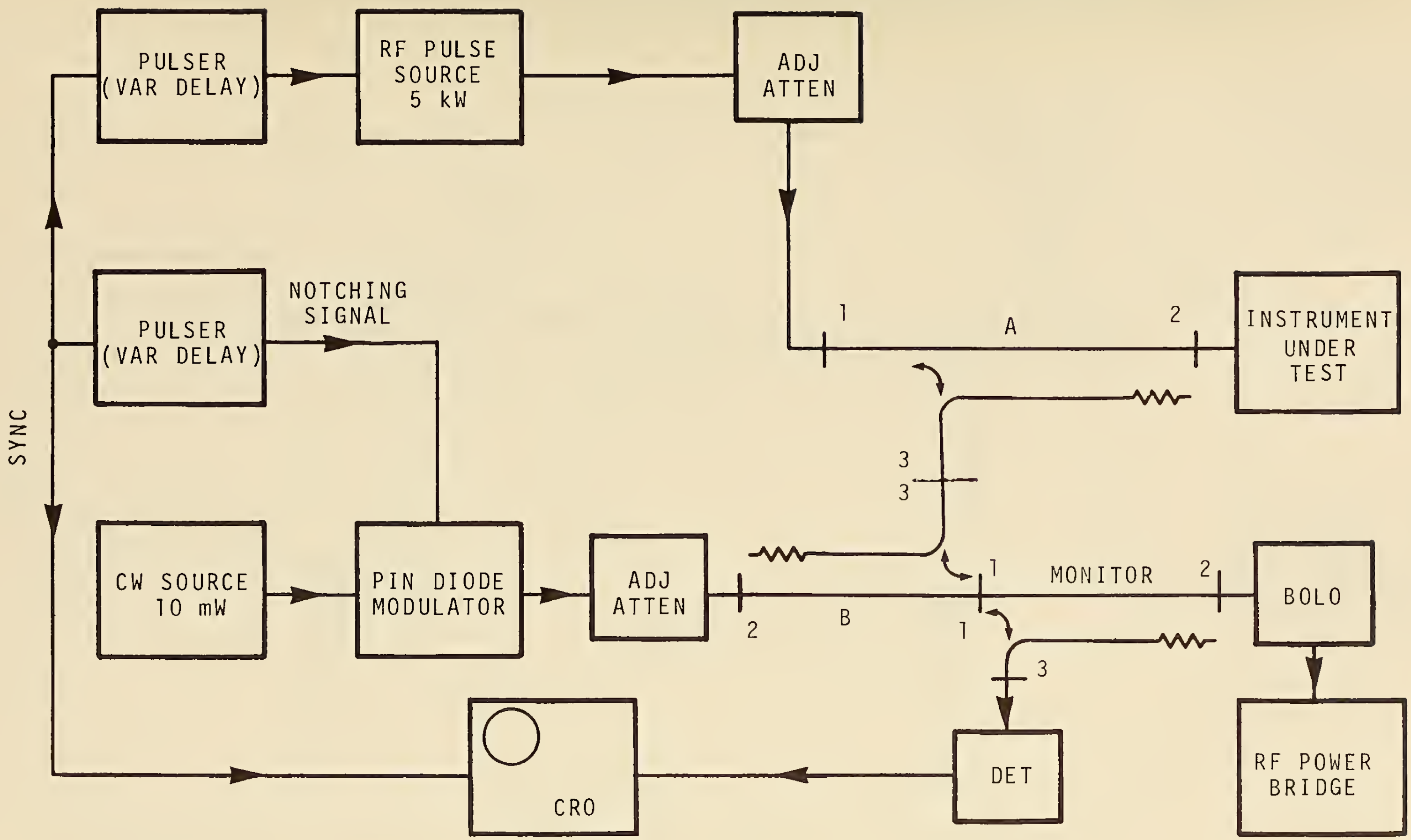

FIGURE 1a. CONFIGURATION FOR CALIBRATING HIGH LEVEL PEAK PULSE POWERS.

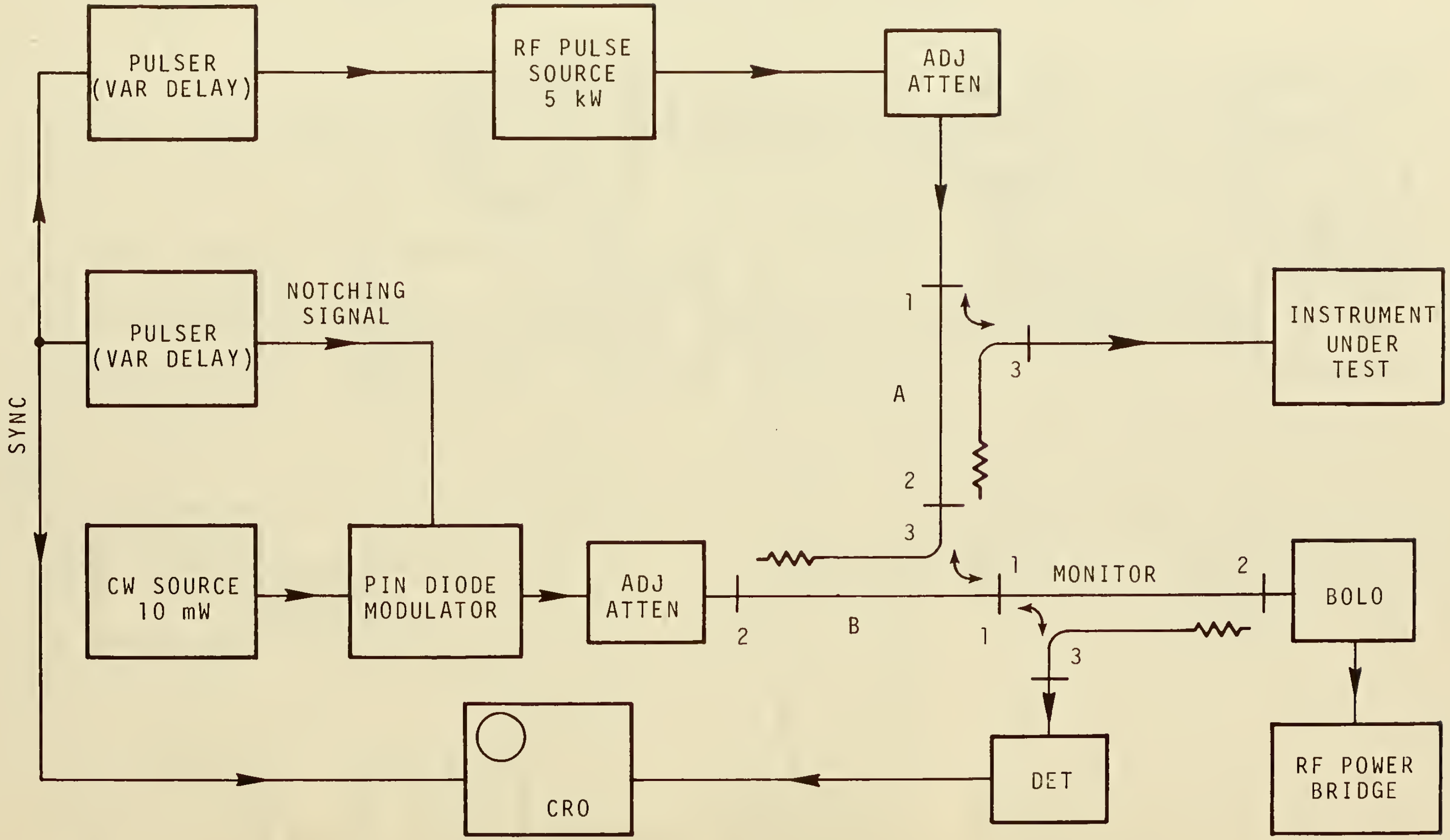

FIGURE 1b. CONFIGURATION FOR CALIBRATING LOW LEVEL PEAK PULSE POWERS.

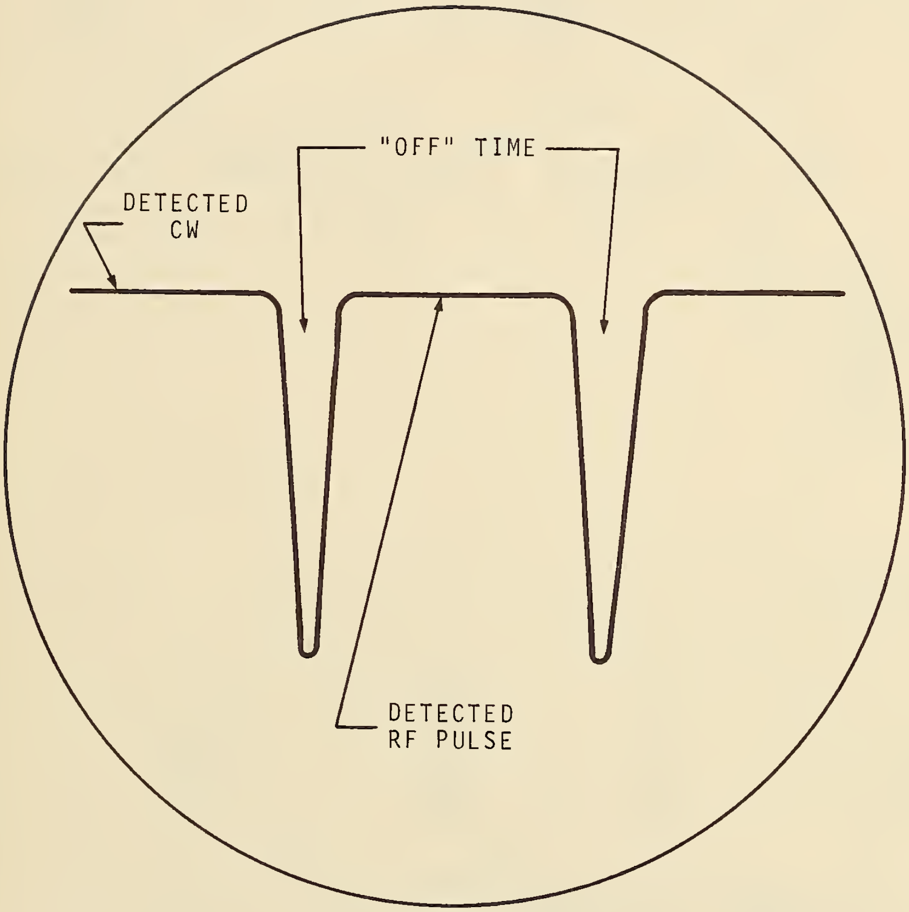

FIGURE 2. IDEALIZED PATTERN SEEN ON MONITOR OSCILLOSCOPE.

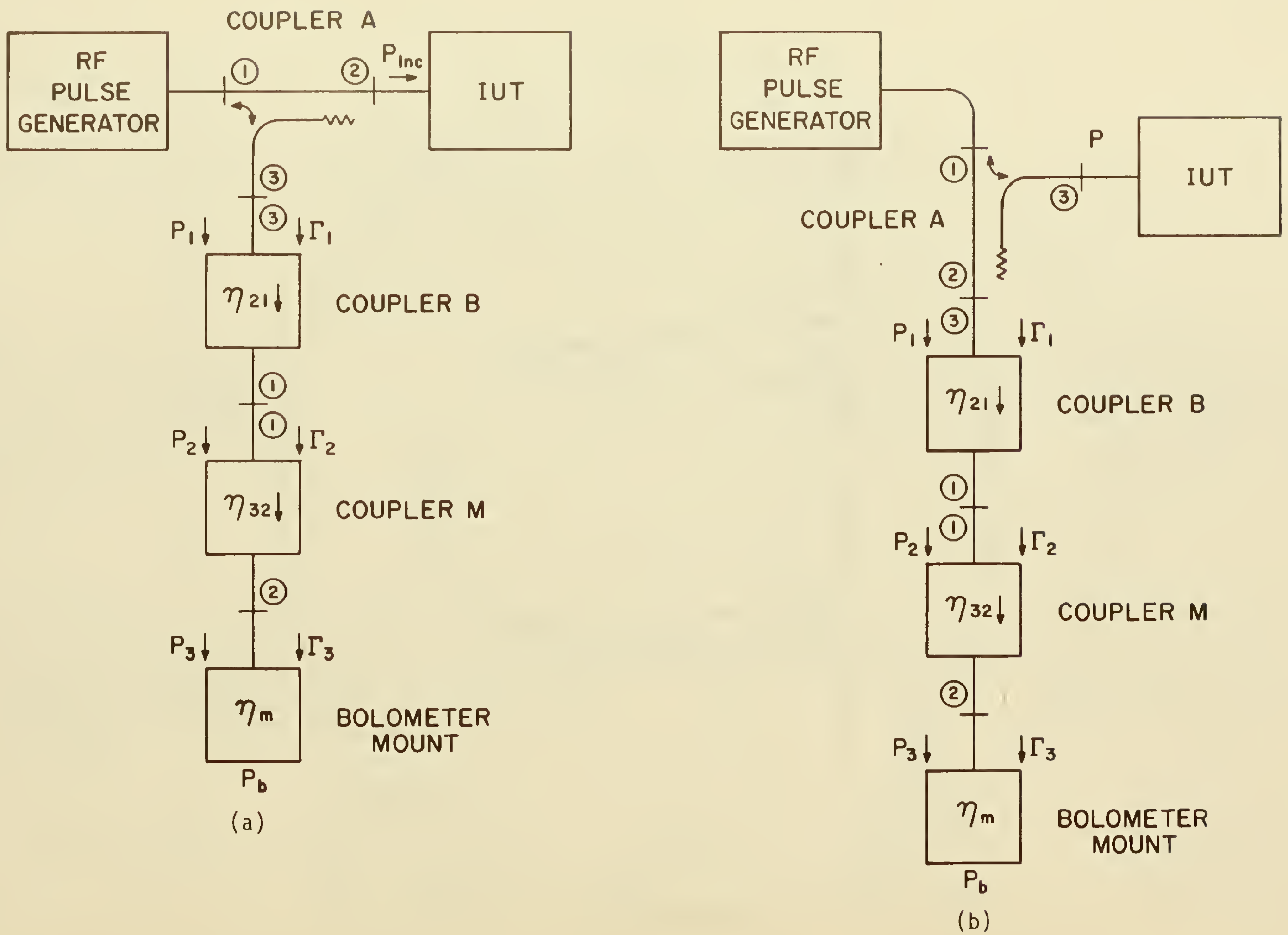

FIGURE 3. EQUIVALENT BLOCK DIAGRAM OF SYSTEM
(a) HIGH POWER CONFIGURATION
(b) LOW POWER CONFIGURATION

We begin by writing

$$P_{inc} = K_A(\Gamma_1)\cdot P_1 \tag{1}$$

where $K_A(\Gamma_1)$ is the output to sidearm coupling ratio of coupler A when its sidearm is terminated in a load having reflection coefficient Γ_1. As implied by the notation K_A has a functional dependence on Γ_1. It is also dependent upon Γ_{IUT} but this aspect will be addressed later. For the present it is assumed $\Gamma_{IUT} = 0$. Multiplying and dividing eq (1) by $(P_2\cdot P_3\cdot P_b)$ yields

$$P_{inc} = K_A(\Gamma_1)\cdot \frac{P_1\ (P_2\cdot P_3\cdot P_b)}{(P_2\cdot P_3\cdot P_b)} \ . \tag{2}$$

Now,

$$P_2 = P_1\cdot \eta_{21}$$

$$P_3 = P_2\cdot \eta_{32}$$

$$P_b = P_3\cdot \eta_m$$

so that

$$P_{inc} = \frac{K_A(\Gamma_1)\cdot P_b}{\eta_{21}\cdot \eta_{32}\cdot \eta_m} \tag{3}$$

Equation (3) establishes the relationship between P_{inc} and P_b, the power measured by the bolometric power meter. The terms K_A and η_{21} are coupling ratios, η_{32} is the insertion loss of coupler M, and η_m is the effective efficiency of the bolometer mount.

Equation (3) suggests that a wide range of pulse power can be measured with a much narrower range of CW power by judicious combinations of coupling values for A and B (K_A and η_{21}). This is done in actual practice. By using the various combinations of directional couplers listed in table 1, peak powers from 10 μW to 10 kW (90 dB range) can be measured with CW powers in the range 1 to 10 mW.

Theoretically, the limits could be extended indefinitely, but certain factors such as signal-to-noise ratio on the lower end and voltage breakdown of components on the high end place practical restraints on how wide a range can be covered.

Table 1a. Values of Directional Couplers for Measuring Peak Powers Greater than 1 Watt (Refer to Figure 1a).

Power Level	Coupler A	Coupler B
1 kW - 5 kW	40 dB	20 dB
0.1 kW - 1 kW	30 dB	20 dB
10 W - 100 W	20 dB	20 dB
1 W - 10 W	10 dB	20 dB

Table 1b. Values of Directional Couplers for Measuring Peak Power Less than 1 Watt (Refer to Figure 1b).

Power Level	Coupler A	Coupler B
0.1 W - 1 W	10 dB	30 dB
10 mW - 100 mW	10 dB	20 dB
1 mW - 10 mW	20 dB	20 dB
100 μW - 1 mW	30 dB	20 dB
10 μW - 100 μW	40 dB	20 dB

As thus far described, the system calibrates terminating type instruments. By rearranging the position of several components the calibration of feed-through meters can also be accomplished. When using the high power configuration, the output port of the IUT is connected to the input port of coupler A. For low power, feed-through IUT's the device itself replaces coupler A, and its output port is connected to the coupled port of coupler B. With these arrangements of components, the <u>input</u> to sidearm coupling ratio of coupler A is required.

It should be noted that the arrangement for measuring low power, feed-through IUT's limits the minimum, measurable peak power to approximately twice the power of the notched CW signal (coupler B = 3 dB). It might be possible to measure smaller peak powers by interchanging the signal inputs to coupler B, but since feed-through peak power meters in this range are not commonplace, the matter of their measurement will not be considered.

2.2 Attractive Features of the Notch Wattmeter

The notch wattmeter technique was chosen as the basis for the standard because of several attractive features which are inherent to the method. These are:

1. the measurement of rf peak pulsed power is directly related to a CW power measurement which can be performed accurately and conveniently;
2. it is independent of pulse shape;
3. it is capable of measuring short duration pulses;
4. it is possible to make measurements on pulse trains with either constant or time varying repetition rates;
5. it is relatively easy to extend the technique to higher microwave frequencies as required.

It is primarily because of the added advantage of the latter three points that this technique was chosen to replace the earlier sampling-comparison method.

3. DESCRIPTION OF THE STANDARD

3.1 Coaxial System

A coaxial system is used as the standard at lower microwave frequencies*. Figure 4 shows the arrangement of the precision directional couplers which are used to combine the pulsed and notched CW rf signals. They are located in the structure immediately over the sloping front console in the figure. These couplers were developed at NBS [4], and possess excellent characteristics (low VSWR; high directivity; broadband, calculable coupling). Their use results in the reduction of many uncertainties in the measurement process. A complete discussion of the uncertainties is given later in the error analysis in section 4.

Basic theoretical ranges for the various parameters of the system plus some of the practical limits are given in Table 2. Such things as maximum generator output, oscillator frequency range, modulator transition times, and pulser repetition rates impose restrictions which cause a reduction in the actual operating range of the standard.

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*For frequencies in the VHF band, the sampling-comparison method is still employed because of limited demand.

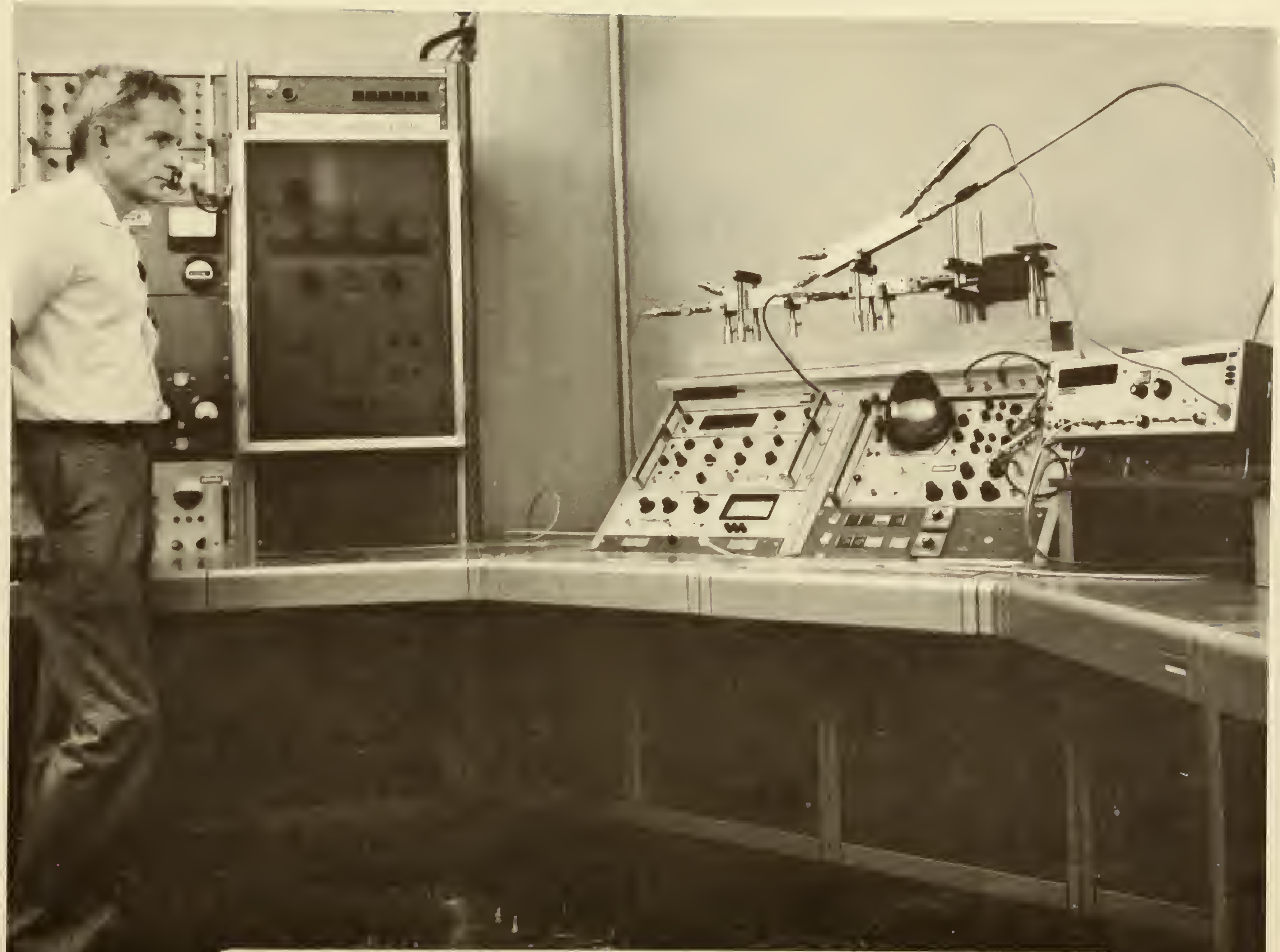


FIGURE 4. COAXIAL NOTCH WATTMETER SYSTEM FOR MEASURING RF PEAK PULSE POWER AT FREQUENCIES UP TO 4.4 GHz.

Table 2. Limits of Operation of Coaxial Notch Wattmeter Standard.

Parameter	Theoretical Range	Practical Range
Frequency	850 to 2350 MHz 2550 to 7000 MHz	950 to 2350 MHz 4000 to 4400 MHz
Peak Power	10 μW to 10 kW	10 μW to 2 to 5 kW[a]
Pulse Duration	$\frac{1}{\text{carrier frequency}}$ to CW	100 nsec to 500 msec[b] 100 nsec to 10 μsec[c]
Pulse Repetition Rate	single shot to $\frac{\text{carrier frequency}}{2}$	100 to 100 k pps[b] 100 to 3 k pps[c]
Duty Factor	0 to 1	1×10^{-5} to 0.5[b] 10^{-5} to 0.0033[c]

a. dependent upon carrier frequency

b. for $P_p < 1$ W

c. for $P_p > 1$ W

3.2 Waveguide System

At higher microwave frequencies a standard has been implemented in WR-90 (8.2-12.4 GHz). The technique, furthermore, is readily extendable to higher or lower frequency waveguide sizes. Figure 5 is a photograph of the X-band system. The CW source is a Gunn diode oscillator. For peak powers up to 1 W, a pulsed signal is derived from the CW signal and amplified by a TWT. Above 1 W a magnetron is used which generates 10 kW peak at certain discrete pulse durations and repetition rates. Except for frequency, the theoretical limits for the various parameters of the waveguide notch wattmeter are the same as those of the coaxial system. Table 3 gives the actual ranges of operation as limited by practical considerations.

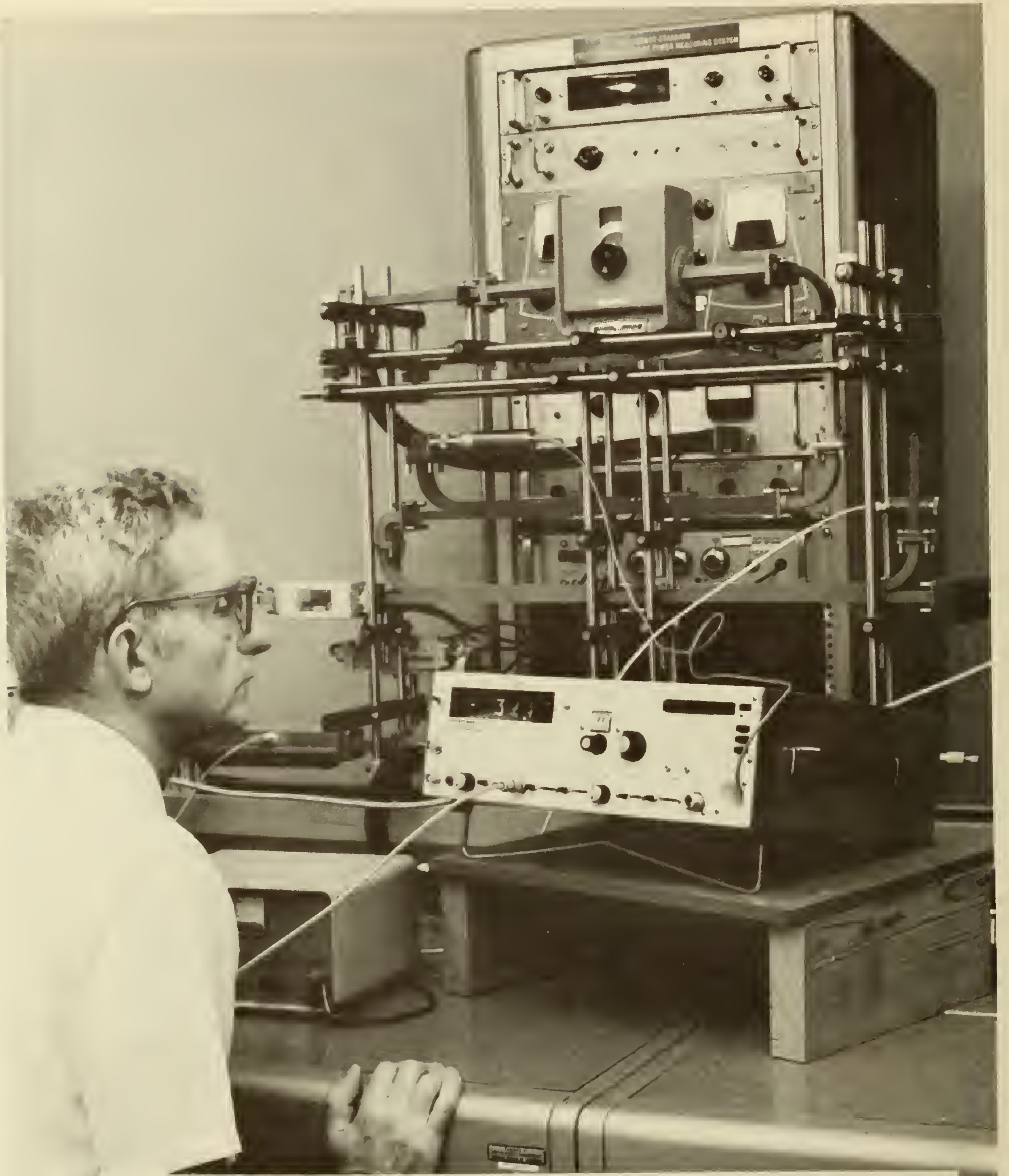


FIGURE 5. WAVEGUIDE NOTCH WATTMETER FOR MEASURING RF PEAK PULSE POWER AT X-BAND.

Table 3. Actual Operating Ranges for X-Band Notch Wattmeter.

Parameter	Current Practical Limited Range
Frequency	8.2 - 12.4 GHz
Peak Power	10 μW - 10 kW
Pulse Duration	100 nsec - 500 msec[a] 250 nsec, 1 μsec[b]
Pulse Repetition Rate	100 - 100 K[a] 100 - 3 K[b]
Duty Factor	1×10^{-5} - 0.5[a] 2.5×10^{-5} - 7.5×10^{-4}[b]

a. for $P_p < 1$ W

b. for $P_p > 1$ W

4. ERROR ANALYSIS

For purposes of analyzing systematic errors, eq (3) can be converted to an alternative form which explicitly exhibits mismatch effects. Also, it is usual practice to measure coupling attenuation of couplers and insertion loss of devices rather than efficiency. Since the coupling ratio of the couplers is measured under nominally matched conditions, we express $K_A(\Gamma_1)$ in terms of $K_A(\Gamma_o)$, (where Γ_o represents a matched load) and the mismatch effect when the sidearm is terminated in a load having a reflection coefficient, Γ_1. Since, $K_A(\Gamma_1) = P_{inc}/P_1$ and $K_A(\Gamma_o) = P_{inc}/P_o$, $K_A(\Gamma_1) = K_A(\Gamma_o)P_o/P_1$.

The ratio P_o/P_1 must now be determined in terms of the Γ's. This can be done by considering the ratio of the mismatch factors for the power delivered by a generator to a matched and a mismatched load. Engen [5] has shown the mismatch factor, $M_{g\ell}$, between a generator, g, and a load, ℓ, is

$$M_{g\ell} = \frac{(1-|\Gamma_g|^2)(1-|\Gamma_\ell|^2)}{|1-\Gamma_g\Gamma_\ell|^2} \tag{4}$$

Thus,

$$\frac{P_o}{P_1} = \frac{M_{g\ell_o}}{M_{g\ell_1}} = \frac{\dfrac{(1-|\Gamma_g|^2)(1-|\Gamma_o|^2)}{|1-\Gamma_g\Gamma_o|^2}}{\dfrac{(1-|\Gamma_g|^2)(1-|\Gamma_1|^2)}{|1-\Gamma_g\Gamma_1|^2}} \tag{5}$$

and since $\Gamma_o = 0$,

$$\frac{P_o}{P_i} = \frac{|1-\Gamma_g\Gamma_1|^2}{(1-|\Gamma_1|^2)} \quad . \tag{6}$$

Substituting the above results in eq (3), we have

$$P_{inc} = \frac{K_A(\Gamma_o)\ |1-\Gamma_g\Gamma_1|^2\ P_b}{(1-|\Gamma_1|^2)\ \eta_{21}\eta_{32}\eta_m} \tag{7}$$

The efficiency of a 2-port can be expressed in form*

$$\eta = \frac{|S_{21}|^2\ (1-|\Gamma_\ell|^2)}{|1-S_{22}\Gamma_\ell|^2\ (1-|\Gamma_{in}|^2)}$$

and the calibration factor, K_b, of the bolometer mount is $K_b = (1-|\Gamma_3|^2)\ \eta_m$. Substituting for the η's in eq (7) yields

$$P_{inc} = P_b \frac{K_A(\Gamma_o)|1-\Gamma_g\Gamma_1|^2|1-S_{22}\Gamma_2|^2(1-|\Gamma_{in_1}|^2)\cdot|1-S_{33}\Gamma_3|^2\cdot(1-|\Gamma_{in_2}|^2)(1-|\Gamma_3|^2)}{(1-|\Gamma_1|^2)\ |S_{21}|^2(1-|\Gamma_2|^2)\ |S_{32}|^2(1-|\Gamma_3|^2)\ K_b} \tag{8}$$

*A suggested text for deriving this expression is "Basic Theory of Waveguide Junctions and Introductory Microwave Network Analysis," by D. M. Kerns and R. W. Beatty, Pergamon Press, New York, N.Y. 11101, 1967. Sections 2.2 through 2.4 are especially helpful.

Noting that $|\Gamma_{in_1}| = |\Gamma_1|$ and $|\Gamma_{in_2}| = |\Gamma_2|$ and substituting the proper S parameters as determined from figure 3 (i.e., $S_{21} = S_{B_{31}}$ and $S_{32} = S_{M_{12}}$) for the S parameters in eq (8) yields

$$P_{inc} = P_b \frac{K_A(\Gamma_o)\cdot|1-\Gamma_g\Gamma_1|^2\cdot|1-S_{B_{11}}\Gamma_2|^2\cdot|1-S_{M_{22}}\Gamma_3|^2}{|S_{B_{31}}|^2\cdot|S_{M_{12}}|^2\cdot K_b} \tag{9}$$

Thus, calculation of P_{inc} from a measurement of P_b requires only the evaluation of the terms in eq (9). The overall systematic uncertainty will, of course, depend upon the uncertainty in evaluating the individual terms.

As noted previously, K_A and $(1/|S_{B_{31}}|)^2$ are power coupling coefficients, i.e., the attenuation with the unused ports terminated with matched loads, of the two directional couplers A and B. The term $(1/|S_{M_{12}}|)^2$ is the attenuation of coupler M, and K_b is the calibration factor of the bolometer mount. The other terms in the equation take into account mismatch effects.

4.1 CW Power Measurement Errors

The CW power is measured with a precision dc power bridge and a thermistor mount whose calibration factor, K_b, is known to an uncertainty limit of 1 percent in coax and 0.9 percent in waveguide. As an alternative to the previous definition, calibration factor for bolometer mounts may be defined as the ratio of the substituted dc power in the mount to the rf power incident upon the mount. The power bridge measures the substituted dc power to an uncertainty limit of 0.2 percent. Mismatch effects may also affect the CW power measurement and this subject will be discussed in section 4.4.

An additional small error in P_b will occur if the "dead" time, which is defined as the difference between the average power removed by the notch and the average power of the rf pulse, becomes significant. Usually, this dead period has an equivalent duration no greater than 1 μsecond per pulse so that repetition rate becomes the dominant factor. Assuming a maximum duration of 1 μsecond, a PRR of 1000 pps will result in 0.1 percent error. However, if necessary this error can easily be eliminated by simply removing the pulsed rf and notching signals, and making a normal CW power measurement immediately after the CW and pulse signals have been matched in amplitude. This operation is valid since tests have shown the CW generator has the necessary stability and the pin diode modulator has the same impedance in the low insertion loss state whether it is being switched or is on continuously.

In summary, the total uncertainty in measurement of the CW power is the sum of the individual uncertainties in K_b and the bridge, and is 1.2 percent for coax and 1.1 percent for waveguide. "Dead" time may or may not be significant, but its effect can be eliminated if necessary.

4.2 Coupling Factors of Couplers A and B

The accuracy with which the coupling factor of the two directional couplers, A and B, is known has a direct bearing on the overall accuracy of the pulsed rf power measurement. The manner in which the factors are determined is somewhat different for the two systems.

In the coaxial system the couplers are a precision type as mentioned previously. The VSWR is 1.03 or less and the coupling value is calculable to a high degree of accuracy from the theoretical equation

$$K_f = K_o \frac{1}{\sin^2 \frac{\pi}{2} \frac{f}{f_o}} \tag{10}$$

where

K_f = the coupling at frequency f expressed as a power ratio;

K_o = the value of maximum coupling expressed as a power ratio;

f = the frequency at which K_f is to be determined;

f_o = the frequency at which K_o occurs.

K_o and f_o in this equation are determined by measuring K_f at 4 or 5 frequencies in the range of 900 to 2000 MHz and fitting eq (10) to the data. K_f values can be determined at NBS to 0.5 percent using the method described by Bramall [6]. For these couplers f_o lies in the vicinity of 1.4 GHz, and over the stated frequency range measured values of K_f are within 0.25 percent of calculated values.

The couplers are also usable in the region of $f = 3\ f_o$. However, their coupling values, K_f, cannot be calculated with the necessary accuracy, but must be determined by power ratio measurements at the desired frequency. The uncertainty associated with these measurements is also 0.5 percent.

In contrast to coax waveguide couplers are not calculable but are measured at each frequency of interest by the Bramall method. The uncertainty of these measurements is 0.02 dB/10 dB for values up to 30 dB and 0.03 dB/10 dB for 40 dB.

Thus the uncertainty for these couplers is as follows:

10 dB - 0.46%

20 dB - 0.93%

30 dB - 1.39%

40 dB - 2.80%

Since the coupling factors of coupler A and B were measured using CW signals, the question arises as to whether the coupling will be different for pulsed signals whose carrier frequency is the same as the CW signal. The pulse signals are, of course, broadband. As shown in figure 6, the spectrum includes components of significant amplitude out to the 7th side-lobe for a 950 MHz, 0.1 μs pulse having 10 ns risetime. Thus, the total bandwidth of the signal extends ±70 MHz on each side of the carrier frequency.

FIGURE 6. RELATIVE LINEAR AMPLITUDE SPECTRUM OF 950 MHz,
0.1 μs PULSE.

The power coupling is not linear with frequency, but varies relative to the coupling at f_o as $1/\sin^2(f/f_o)$. When the carrier frequency, f_c, is equal to f_o, then the coupling of the side-lobe frequencies will be symmetrical. In the NBS coaxial system, f_c varies from 950 to 2000 MHz and the f_o of the couplers is 1400 MHz. The maximum variation in coupling for the 950 MHz pulse described above is -1.7 percent (+8.6% and -10.3%) and some distortion in the detected pulse could be expected. The question is whether the amplitude of the detected pulse would be affected because we are comparing amplitudes of the detected CW and the pulse.

In an attempt to answer this question, an experiment was performed wherein the 950 MHz, 0.1 μs pulse amplitude was compared after it had been coupled to the sidearm of a 20 dB coupler and after it had passed through a broadband (dc-18 GHz) 20 dB attenuator pad having the same loss as the coupler at 950 MHz. From photographs of the two detected pulses on an oscilloscope crt, the two amplitudes appeared identical within the limits of resolution (1/4 trace width) as shown in figure 7.

As a confirmation of this finding, a series of approximate calculations were performed. The maximum amplitude of the main lobe and the ten upper and lower side lobes of the $\frac{\sin x}{x}$ envelope of the spectrum of an rf pulse were squared, then multiplied by the value of coupling at their corresponding frequencies, and summed. This value was compared against the sum of squared, undistorted amplitudes. The calculations were performed for pulses of several durations. The results showed a difference of less than 0.01 percent for durations as short as 100 ns. For a 14 ns rectangular pulse the difference was 0.75 percent.

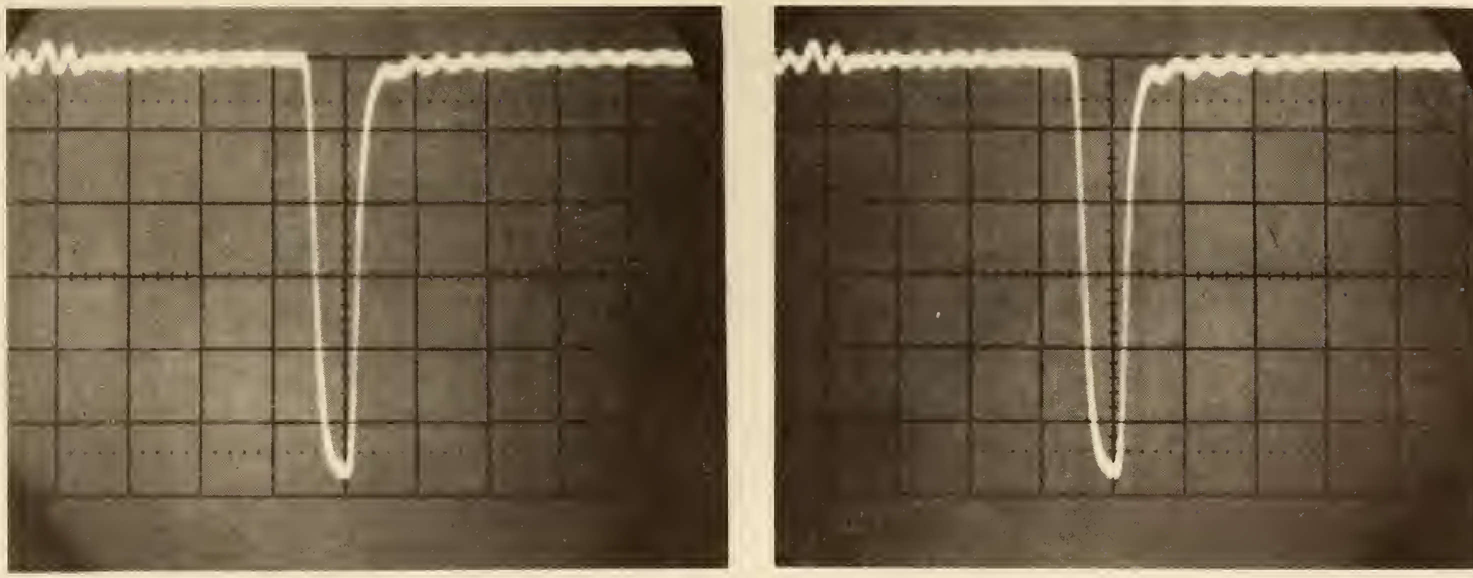
It is concluded that for pulses having a minimum duration of 100 ns and 10 ns risetime, the effect of the couplers on the pulse amplitude is negligible.

4.3 Attenuation of the Monitor Coupler

The directional coupler used as the monitor has a nominal coupling factor of 10 dB. This value is used to provide sufficient sensitivity for the pulse-CW intercomparison while minimizing the power coupled from the measuring circuit. The monitor couplers used in the coaxial and waveguide systems are similar to couplers A and B in their respective systems. The uncertainty in their measured values of attenuation (nominally 1.1) is 0.1 percent.

4.4 Impedance Mismatch Errors

As shown in eq (9), the relationship between P_b and P_{inc} is modified by impedance mismatch effects denoted by the terms $|1-\Gamma_g\Gamma_1|^2$, $|1-S_{B_{11}}\Gamma_2|^2$ and $|1-S_{M_{22}}\Gamma_3|^2$. Evaluation of the above terms would require knowledge of both the magnitude and phase of the Γ's and S's. In practice, only the magnitudes are known and, thus, upper and lower limits of the terms are established by using both the plus and minus signs. The terms are then written as $|1\pm\Gamma_g\Gamma_1|^2$, $|1\pm S_{B_{11}}\Gamma_2|^2$, and $|1\pm S_{M_{22}}\Gamma_3|^2$. Since the value of each term is centered around unity, the maximum diviation from unity is taken as the mismatch uncertainty.



a b

FIGURE 7. COMPARISON OF DETECTED 950 MHz PULSE ENVELOPE AMPLITUDE AFTER ATTENUATION BY A 20 dB COUPLER (A) AND BY A 20 dB BROADBAND PAD (B).

Further, the terms appear as a product in eq (9) and the total mismatch uncertainty is the product of the maximum deviations from unity.

We can then write an uncertainty factor, γ, given by

$$\gamma = |1 \pm \Gamma_g \Gamma_1|^2 \cdot |1 \pm S_{B_{11}} \Gamma_2|^2 \cdot |1 \pm S_{M_{22}} \Gamma_3|^2 \tag{11}$$

An evaluation of the Γ's and S's follows.

Γ_g is the equivalent generator impedance of coupler A and is independent of the pulsed rf generator and any external components such as isolators, filters, attenuators, etc. This is a result of the method used whereby changes in the power entering coupler A are compensated for so that a constant reading is maintained on the IUT. Engen [7] has shown that under this condition Γ_g is given by

$$\Gamma_g = (S_{22} - S_{12} \cdot \frac{S_{23}}{S_{13}}) \tag{12}$$

where $S_{x,y}$ are the scattering coefficients of the coupler. Note in this setup the subscripts 1, 2, and 3 refer to the input port, the port connected to coupler B, and the port connected to the IUT, and the actual ports represented by 2 and 3 are reversed when changing from the high power to the low power configuration. For coax maximum $|\Gamma_g|$ occurs in the low power configuration. In this case $|\Gamma_g| = \pm 0.0248$ ($|S_{22}| = 0.0148$, $|S_{12}| \simeq 1.0$, $|S_{23}/S_{13}| = 0.01$). For waveguide, maximum $|\Gamma_g|$ is in the high power configuration. Here $|\Gamma_g| = \pm 0.0508$ ($|S_{22}| = 0.0476$, $|S_{12}| = 0.3162$, $|S_{23}/S_{13}| = 0.01$).

We will now evaluate the other Γ's in a direction from the bolometer mount toward the coupler A-coupler B junction. The reflection coefficient of the bolometer mount (Γ_m) equals ± 0.0476 for both coax and waveguide.

The term Γ_2 is the actual reflection coefficient encountered at the input of coupler M and is affected by the Γ of the bolometer mount and to a lesser degree by that of diode detector. The high directivity (40 dB) of this coupler (and coupler B) renders insignificant any contribution from the decoupled port. The maximum value of $|\Gamma_2|$ can be calculated by solving the scattering equations for a three arm junction; thus, using the approximate relation

$$|\Gamma_{in}| \leq |S_{11}| + \frac{|S_{12}|^2 \ |\Gamma_2|}{1 - |S_{22}\Gamma_2|} + \frac{|S_{13}|^2 \ |\Gamma_3|}{1 - |S_{33}\Gamma_3|} \tag{13}$$

where $S_{x,y}$ are again the scattering coefficients of the coupler and Γ_y is the reflection coefficient seen by port y. Values to be used in eq (13) to solve for Γ_2 in eq (11) are for coax $|S_{11}| = |S_{22}| = |S_{33}| = 0.0148$, $|\Gamma_2| = 0.0476$ (bolometer), $|\Gamma_3| = 0.0476$ (detector), $|S_{12}|^2 = 0.9$, and $|S_{13}|^2 = 0.1$. These give $|\Gamma_2|$ (for eq (11)) = ± 0.0624. For waveguide

$|S_{11}| = |S_{22}| = 0.0244$, $|S_{33}| = 0.0476$, $|\Gamma_3| \simeq 0.0$ (detector is tunable), and $|S_{12}|^2 = 0.9$. These give (for waveguide) $|\Gamma_g| = \pm 0.0673$.

Equation (13) is also used to determine an upper limit for Γ_1 in eq (11). In this case the input port is what is usually referred to as the coupled port. For coax, $|S_{11}| = |S_{22}| = |S_{33}| = 0.0148$, $|\Gamma_2| = 0.0148$, $|\Gamma_3| = 0.0624$, $|S_{12}|^2 = 0.99$, and $|S_{13}|^2 = 0.01$. These yield $|\Gamma_1| = \pm 0.0154$. For waveguide the input arm is terminated internally. The reflection coefficient at the input, with all the other ports terminated in matched loads, is 0.0476. This then is the contribution to Γ_{in} of eq (13) by the first two terms. For the third term $|\Gamma_3| = 0.0673$, $|S_{13}|^2 = 0.01$, and $|S_{33}| = 0.0246$. The maximum value of $|\Gamma_1| = \pm 0.0483$ for waveguide.

A value for γ can now be determined from eq (11). Using the double signed terms we find for coax $0.9960 \le \gamma \le 1.0040$ and for waveguide $0.9895 \le \gamma \le 1.0106$. Similar treatment for the other two cases yields $0.9962 \le \gamma \le 1.0038$ for low power coax, and $0.9911 \le \gamma \le 1.0090$ for high power waveguide.

Thus the maximum uncertainty introduced by mismatch effects is

Coax	
Low power configuration	±0.38%
High power configuration	±0.40%
Waveguide	
Low power configuration	±1.06%
High power configuration	±0.90%

Some discussion of the effect on the system of a mismatched IUT should be made at this point, since in section 2.1 Γ_{IUT} was assumed to be 0. The first order deviation of P_{inc} from the value associated with $\Gamma_{IUT} = 0$ is accounted for by defining the response of the IUT as that instrument's performance when operating in a system of characteristic impedance Z_o. The error in P_b caused by the power reflected from the IUT is insignificant because of the 40 dB directivity of coupler A. For instance, if $|\Gamma_{IUT}| = 0.2$ (VSWR = 1.5) then 4 percent of the power is reflected, which in turn is attenuated 40 dB resulting in 0.0004 percent error. This reasoning on the latter point also requires that the diode detector on coupler M has a square law response to avoid the possibility of small but significant errors in the intercomparison of the pulsed and notched CW signals.

4.5 Bandwidth-Risetime Limitations

One factor which limits the bandwidth of the system (and hence sets a minimum risetime for pulses) is the risetime of the oscilloscope and the diode detector combination. The risetime of the combination was measured by applying the output of a tunnel diode step generator having a risetime of 25 ps to the diode and observing the output on the system oscilloscope. The observed risetime was 8 ns. Since the input step was nearly three orders

of magnitude faster than the output from the combination, the above value was taken as the true risetime. While diodes and oscilloscopes with faster risetimes are available, the ones used here are adequate for present needs.

4.6 On/Off Ratio of the Diode Modulator and Pulse Generator

If any CW power leaks through the diode notching modulator while it is in the "off" (high isolation) mode, the unwanted CW will add to the pulse causing an incorrect amplitude. This, in turn, will cause the P_b to be in error when it is intercompared with the pulse.

Manufacturer's specifications for the modulators used in both the coax and waveguide systems quote 80 dB isolation. Tests performed sensitive to 0.01 percent of the power in the "on" condition showed no detectable leakage of the CW signal during the time period when it is "notched" off. Thus, the leakage signal is no greater than 0.01 percent of the CW power and is, therefore, negligible.

Inadequate on/off ratio in the pulse power generator would also cause an error because any signal in the off condition would add to the CW signal from the low power generator. The pulse power generator employs a single tube pulsed oscillator and the output is zero in the interval between pulses.

4.7 Leakage of the CW Signal into the Device Being Calibrated

Even though directional couplers A and B are placed in the system backwards with respect to the CW signal, it is possible for some of the CW power to find its way into the IUT since their directivity is not infinite but approximately 40 dB.

An analysis of the arrangement of couplers A and B reveals the CW signal that leaks into the IUT is attenuated by the same attenuating elements for both configurations. The CW attenuation is given by the expression

$$A = K_B + D_B + K_A + D_A \tag{14}$$

where

A = attenuation in dB of the CW signal

K_B = coupling factor of coupler B in dB

D_B = directivity of coupler B in dB

K_A = coupling factor of coupler A in dB

D_A = directivity of coupler A in dB

Worst case conditions occur for the low power configuration with coupler B equal to 20 dB. Calculations show that with the 40 dB directivity of couplers A and B, the CW is reduced to a level 100 dB below the peak power of the pulsed signal and is thus negligible.

4.8 Precision of CW-Pulse Intercomparison/Equalization Process

The precision with which the CW and pulse amplitudes can be made equal by visual observation on the oscilloscope crt is a function of the ratio of the trace width to the signal amplitude in centimeters on the crt. Normally, the scope vertical gain is set at its maximum. When the pulse and CW signals are at 1 mW level (worst case) the deflection on the crt is 6.5 cm while the trace width is 0.15 cm (1.5 mm). Under these conditions, the CW amplitude can be adjusted to that of the pulse with a precision of at least a quarter of a trace width. Thus, the imprecision is $\frac{0.25 \times 0.15}{6.5} = 0.57$ percent. This value agrees very closely with an experiment repeatability of 0.58 percent (3σ). This value was the maximum that was observed for sets of 10 readings each made at several frequencies in both coax and waveguide.

In practice, the amplitudes are equalized 6 times and the CW power is measured after each time. The average of the 6 power measurements is computed and this value is used in eq (1) and (2). The averaging process reduces the imprecision to 0.16 percent (2σ). When the signals are at the 10 mW level, the imprecision in the equalization process decreases to approximately 0.10 percent (2σ).

4.9 Repeatability from Setup to Setup

Since the directional couplers are frequently changed to cover different levels of power, there is the possibility of an error being introduced associated with the connection of different couplers into the setup. This error could result from connector non-repeatability or from misalignment of the directional couplers.

To determine the magnitude of this effect, coupler A was taken out of the system and then replaced. While the coupler was out of the setup, the supports were moved. The coupler was then connected back into the system with normal care taken to ensure proper alignment and the supports repositioned. Readings were taken before and after the coupler was removed.

For both the coaxial standard and the waveguide standard this operation was performed for six connections. In the coaxial system the repeatability was 0.09 percent (2σ) and in waveguide it was 0.15 percent (2σ).

4.10 Other Factors Affecting System Stability

The long-term stability of the system is affected by various factors even when the physical arrangement of the component parts is left undisturbed. The more prominent factors have been identified and steps taken to reduce their effect. For instance, temperature has an effect on stability and therefore, room temperature is maintained at 23.5°C ± 0.5°C. Also, an effect attributable to line voltage fluctuations has been noted. The magnitude of the effect has been reduced by operating certain critical pieces of equipment, such as generators, the rf bridge, and the intercomparison oscilloscope, from a regulated ac power line maintained at 115 V ± 0.2 V.

5. SUMMARY OF ERRORS FOR EXISTING RANGES OF OPERATION

5.1 Coaxial System

The systematic error for the coaxial system in the frequency range of .95 GHz to 2.35 GHz and 4 to 4.4 GHz is as follows:

1.	CW power measurement	1.20%
2.	Mismatch error	.40%
3.	Coupling factor of directional couplers A and B	1.00(.50 ea)%
4.	Insertion loss of monitor coupler	.10%
	Total systematic error	2.70%

The random error associated with the coaxial system is essentially the same for all frequency ranges covered. The component parts and their magnitudes are:

1.	Precision of CW pulse intercomparison	0.16%
2.	Repeatability from setup to setup	0.09%

The total random error is best estimated by the RMS sum of these values and is equal to 0.18 percent.

The estimated maximum uncertainty associated with the coaxial system is the sum of the systematic and random errors and equals 2.88 percent.

5.2 Waveguide System

The systematic error in the WR-90 waveguide system is as follows:

1.	CW power measurement	1.10%
2.	Mismatch error	1.06%
3.	Coupling factor of directional couplers A and B	1.39% - 3.73%
4.	Insertion loss of monitor coupler	.10%
	Total systematic error	3.65% - 5.99%

The random errors associated with the waveguide system are caused by the same factors as in the coaxial system. Their magnitudes are:

1.	CW-pulse intercomparison precision	0.16%
2.	Repeatability from setup to setup	0.15%

The total random error for the waveguide system is the RMS sum of these values, and is equal to 0.22 percent.

The maximum error of the waveguide system is the sum of the systematic and random errors and is within the range of 3.87 to 6.21 percent, the exact value being dependent on the directional couplers being used.

6. REFERENCES

[1] Hudson, P. A., Ecklund, W. L., and Ondrejka, A. R., Measurement of rf peak-pulse power by a sampling-comparison method, IRE Trans. on Instrumentation, Vol. I-11, Nos. 3 and 4, December 1962.

[2] Peak-pulse power calibrations initiated, NBS Technical News Bulletin, pp. 212-213, December 1965.

[3] Bowman, D. R., The notch wattmeter, Proc. Nat'l Electronics Conference, Vol. II, pp. 361-371, October 1946.

[4] Hudson, P. A., A high directivity, broadband coaxial coupler, IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-14, No. 6, pp. 293-294, June 1966.

[5] Engen, G. F., An improved method for microwave power calibration with application to the evaluation of connectors, Jour. of Research of the National Bureau of Standards-C Engineering and Instrumentation, Vol. 75C, No. 2, pp. 88-93, April-June 1971.

[6] Bramall, K. E., Accurate microwave high power measurements using a cascaded coupler method, Jour. of Research of the National Bureau of Standards-C Engineering and Instrumentation, Vol. 75C, Nos. 3 and 4, July-December 1971.

[7] Engen, G. F., Amplitude stabilization of microwave signal source, IRE Trans. on Microwave Theory and Techniques, Vol. MTT-6, pp. 202-206, April 1958.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The theory and operation of a standard for measuring rf peak pulse power is described. The standard is based on the "notch" principle. It is constructed in coax for frequencies up to 4.4 GHz, and in WR-90 waveguide (8.2-12.4 GHz). The basic range is 1 to 10 mW but is extendable to cover 10 μW to 10 kW using directional couplers. Risetime of the system is 14 nanoseconds. A comprehensive error analysis is given. The uncertainty in coax is 3 percent and in waveguide is 4 to 6 percent depending upon peak power level.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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